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Developing Highway Capacity Manual Capacity Adjustment Factors for Connected and Automated Traffic on Freeway Segments

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Abstract

Connected and automated vehicles (CAVs) will undoubtedly transform many aspects of transportation systems in the future. In the meantime, transportation agencies must make investment and policy decisions to address the future needs of the transportation system. This research provides much-needed guidance for agencies about planning-level capacities in a CAV future and quantify *Highway Capacity Manual* (HCM) capacities as a function of CAV penetration rates and vehicle behaviors such as car-following, lane change, and merge. As a result of numerous uncertainties on CAV implementation policies, the study considers many scenarios including variations in parameters (including CAV gap/headway settings), roadway geometry, and traffic characteristics. More specifically, this study considers basic freeway, freeway merge, and freeway weaving segments in which various simulation scenarios are evaluated using two major CAV applications: cooperative adaptive cruise control and advanced merging. Data from microscopic traffic simulation are collected to develop capacity adjustment factors for CAVs. Results show that the existence of CAVs in the traffic stream can significantly enhance the roadway capacity (by as much as 35% to 40% under certain cases), not only on basic freeways but also on merge and weaving segments, as the CAV market penetration rate increases. The human driver behavior of baseline traffic also affects the capacity benefits, particularly at lower CAV market penetration rates. Finally, tables of capacity adjustment factors and corresponding regression models are developed for HCM implementation of the results of this study.

Transportation in recent years has witnessed the development of advanced technologies in the form of Connected and Automated Vehicle (CAV) systems, with safety and mobility applications being integrated into vehicles and infrastructure to enhance the performance of transportation systems. While the majority of the technical aspects are being handled by the private sector, state and federal institutions are working steadfastly toward the deployment of this suite of emerging technologies as part of intelligent transportation systems, particularly for their transportation systems management and operations (TSMO).

CAVs are undoubtedly set to transform many aspects of transportation systems. However, there are still many uncertainties about future implementation. Meanwhile, transportation agencies must make investment and policy decisions to address the future needs of the transportation system. Long-range transportation plans, municipal transportation plans, regional and system plans, corridor studies, and even traffic impact analyses all rely on multi-year forecasts of travel demand and roadway capacity. Both are presently in flux, as ride-share services are already being linked to an increase in vehicle miles traveled (VMT) while changing CAV headways could cause either an increase or decrease in capacity. But how much will capacity change? If there is to be a capacity increase, will an increase in mainline capacity (shorter headways) be offset by decreasing ramp and merge capacities (shorter and fewer gaps)? Will the capacity change be proportional for both freeways and arterial streets?

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The effects of CAVs have been documented in previous studies. Ye and Yamamoto (*1*), showed that the gradual penetration of CAVs changes the traffic flow dynamics and increases capacity. Wang et al. (*2*) studied the effect of connected automated driving on traffic capacity using a cellular automata model and reiterated similar results from past studies stating that when penetration of CAVs is low, improvement is not significant, but with an increasing penetration rate, capacity increases with accelerative rates.

There have been studies also pointing out the capability of CAVs to stabilize and smoothe out traffic flow. This illustrates the benefits of coordination between CAVs in congested traffic. For instance, Delis et al. (*3*) proposed two macroscopic approaches to modeling adaptive cruise control (ACC) and cooperative adaptive cruise control (CACC) dynamics in traffic flows. The results of both approaches showed that ACC and CACC-equipped vehicles were capable of stabilizing flows with respect to on-ramp perturbations. String stability analysis conducted by Talebpour and Mahmassani (*4*) also provided the same results, stating further that CAVs are more effective in preventing shockwave formation and propagation. The benefits of CAVs have been proved not only in relation to capacity or stability, but also fuel savings, efficiency, and safety. CAVs can potentially reduce fuel consumption by 20% (*5*), thereby reducing emissions. Using a more targeted approach, Guo et al. (*6*) established the possibility of realizing up to 32% fuel savings at signalized intersections. By equipping CAVs with speed harmonization capability (*7*), up to 67% safety risk reduction can be obtained.

Of more interest to this study, we consider two freeway CAV applications, which will have the most significant capacity impact: CACC and advanced merging (A.M.). The CACC was an improvement on ACC through V2V and V2I communications to form platoons. The benefits of these communication systems include a more efficient intersection throughput, travel time reduction, as well as reduction in fuel usage and emissions (*8*). Further, with the data collection potential of CAVs about the driving environment, studies have shown that automated driving can potentially decrease traffic congestion by reducing the time headways, thereby enhancing the traffic capacity (*9*). CACC can significantly improve the safety and operations on roadways. At full market penetration, it is possible to realize between 25% and 35% reductions in travel time (*10*) and achieve a 64% improvement in average vehicle delay (*11*). With CACC, throughput enhancement of over 100% can be realized (*12*), and up to 90% and 100% capacity increases can be achieved for basic freeway segments (*13*), and freeway merge segments (*14*), respectively.

A.M. also takes advantage of vehicle communication capability to control the flow at regular congestion locations such as merge and lane drops. Using V2I and V2V technologies, CAVs can signal other vehicles about their intention to merge into the mainline traffic using a communication medium. With this, vehicles trying to merge can identify acceptable gaps on the mainline and make coordinated lane changes. The coordination occurs between both the mainline traffic and merging vehicles, thereby minimizing any merging disturbance. Recent developments in A.M. capability have established the future benefits to derive from implementing A.M. on merge areas. For example, by integrating both lane change and trajectory optimization, a recent study (*15*) obtained a 93% reduction in average delay. Letter and Elefteriadou (*16*) realized as much as a 62% improvement in speed and total travel time in a freeway merge scenario. Pueboobpaphan et al. (*17*) obtained 60% and 75% average travel time improvements under low flow and high flow conditions of merge segments, respectively.

Research Objectives

With numerous emerging technologies, transportation agencies must make investment and policy decisions to address the future needs of the transportation system. Therefore, agencies need to know the potential capacity effects of CAVs to aid their decision-making process with future investments. The Highway Capacity Manual (HCM) is a valuable tool used by practitioners for planning-level assessments of various facilities and corridors and remains widely accepted throughout the industry as a credible source and benchmark for capacity estimation and analysis guidance. However, agencies are faced with shortfalls in HCM guidance pertaining to CAVs since the HCM is silent on the effects of CAVs. This research provides much-needed guidance for agencies about planning-level capacities in a CAV future and quantifies HCM capacities as a function of CAV penetration rates and allowable vehicle "aggressiveness." The research explores and tests CAV and non-CAV interaction and provides guidance to state and local agencies about the sensitivity of key parameters on the final capacities.

This study aims to develop capacity adjustment factors (CAF) for CAVs on various freeway facilities at different levels of traffic demand and market penetration to adapt the use of HCM in analyzing CAV applications. The goal of this research is not only to quantify the effect of CAVs on the basic freeway, merge, and freeway weaving segments, but also to develop tables of CAFs and corresponding a statistical capacity prediction model that can be easily used to assess the effect of different future

CAV implementation policies. The statistical models developed here are expected to be easily adaptable to changes in various parameters as CAVs continually penetrate transportation systems.

The remaining of this paper includes a methodology section, which provides detailed information on the steps taken to achieve the study objective. Following the methodology is the results section providing the outcome of each experimental setup. The section also gives extensive insights into the effect of CAVs on traffic flow. Also, CAF tables and the method for developing the empirical models for predicting the capacity effects of CAVs are provided. Finally, conclusions are given along with possible future research questions.

Methodology

Base Model Development

Three freeway segments were considered in this study, as shown in Figure 1; a basic freeway segment (BFS), a freeway merge segment (FMS), and a freeway weaving segment (FWS). A well-calibrated hypothetical network that reflects the capacity of freeway segments relative to the free-flow speed (FFS) as specified in the HCM allows the flexibility of roadway and traffic characteristics for sensitivity analysis. In this study, we used FFS of 75 mph for all scenarios. For the BFS, two hypothetical three- and two-lane networks were modeled in VISSIM. The FMS was a two-lane mainline network with an on-ramp introduced one mile downstream the start of the network. The acceleration length was designed as 500 ft. Finally, the FWS was a four-lane weaving segment, indicating a three-lane mainline, a single acceleration/deceleration lane, an on-ramp, and off-ramp 1000 ft apart.

To investigate the effects of CAVs under varying base capacities before the introduction of CAVs, BFS was tested with a base (also referred to as a "starting") capacity of 2,400, 2,000, and 1,800 passenger cars per hour per lane (pcphpl). This test was conducted because not all freeway segments have the same capacities, even with similar geometric features, as a result of the external factors such as differences in driver behavior or weather conditions. However, these base capacities were only applied to the BFS. The analyses for the FMS and FWS used starting capacities of 2,400 pcphpl for all scenarios. This was to limit the scope of the study to more common roadway configurations and to be able to analyze more facility types. Also, the base capacity of 2,400 pcphpl is consistent with the HCM recommended value, and therefore results from this study can directly be applied to existing HCM procedures. It should be noted that although the driver behavior used for the BFS, FMS, and FWS targeted 2,400 pcphpl as the base capacity, the actual starting capacities for FMS and FWS were lower as a result of ramp and weaving disturbances.

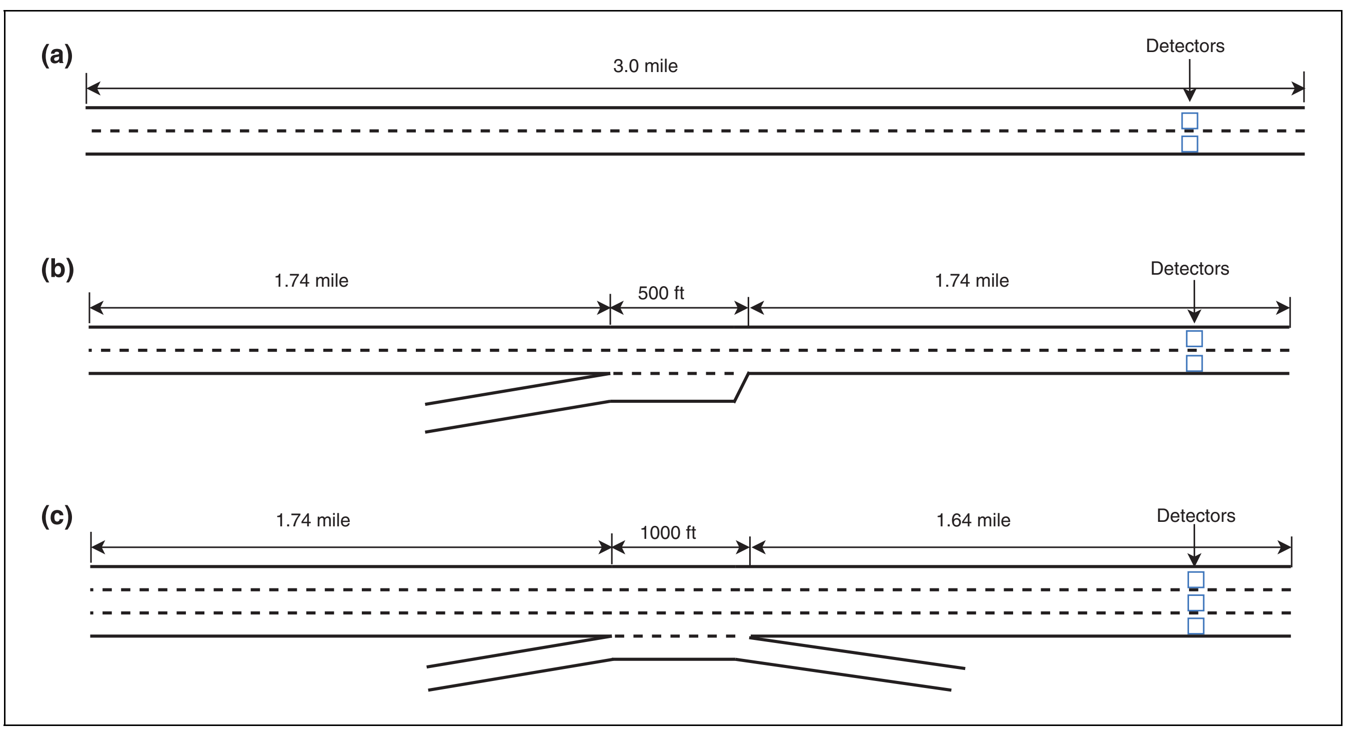

Figure 1. Freeway segments considered: (*a*) basic freeway segment; (*b*) freeway merge segment; and (*c*) freeway weaving segment.

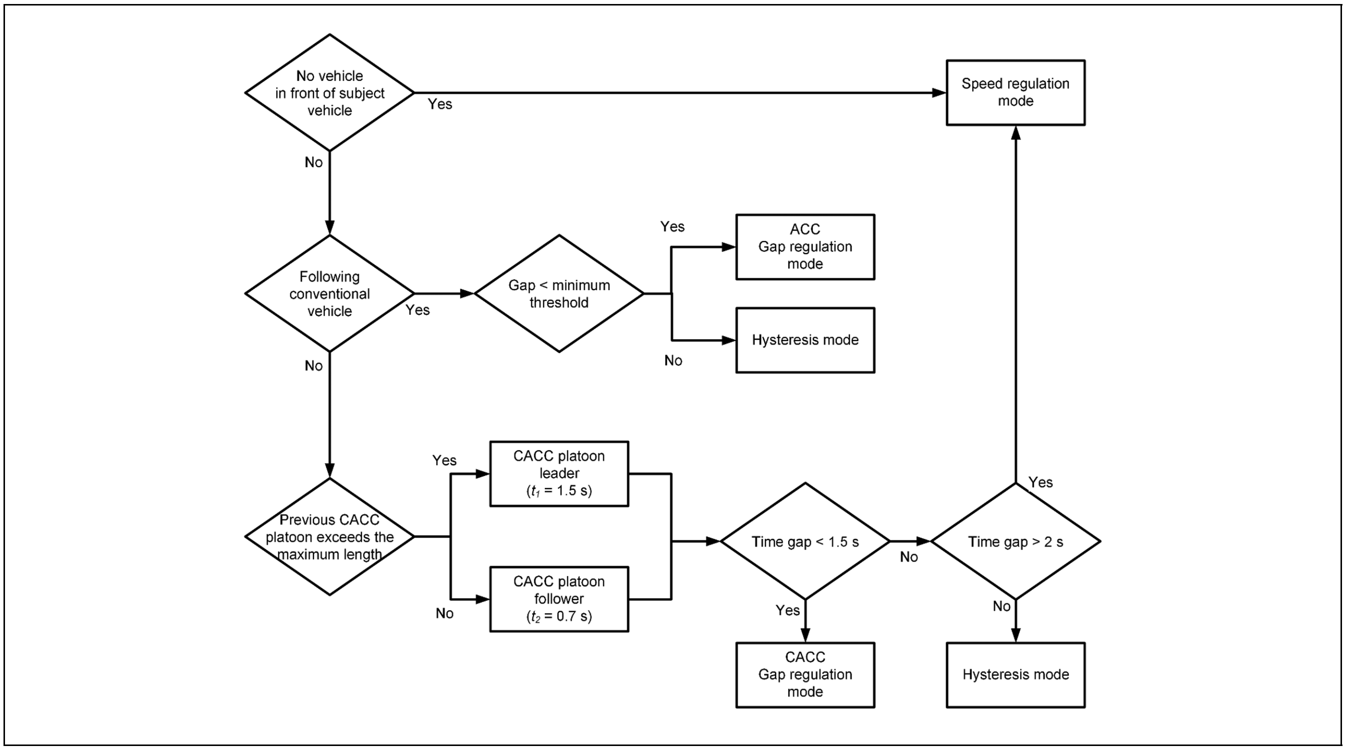

Figure 2. CACC protocol.
Note: CACC = cooperative adaptive cruise control; ACC = adaptive cruise control.

Obtaining the desired capacity for a fully human-driven vehicle (HDV) traffic stream in the microsimulation model requires systematic calibration. The base model was calibrated using the VISSIM in-built driver behavior model developed by Wiedemann (*18*). In this study, the Wiedemann '99 parameters, which are more suitable for freeway networks, were adjusted for calibration (*18*). It provides 10 calibration parameters CC0 to CC9, which control the switching behavior of drivers. The major parameters used were CC0, CC1, and CC2, representing the standstill distance, the headway time, and the following variation, respectively. The targeted starting capacities, as a measure of driver variability, were achieved by adjusting CC2. By adjusting this parameter, the response of drivers to the preceding vehicle is tuned, which in turn affects the prevailing capacity of the simulation network. More detail on these parameters can be found in the PTV VISSIM user's manual (*19*). For all scenarios, CC0 = 1.5 m, CC1 = 1.05 s, and CC2 = 5.0 m, 11-m, and 16-m for base capacities 2,400, 2,100, and 1,800 pcphpl, respectively.

For each scenario, five simulation replications with different random seeds were performed. The result for each scenario was averaged over the replications. The input volume was gradually increased and then decreased in such a way that the simulation experiments were able to capture the free flow and the breakdown regimes over the simulation period. This allows the system throughput to level off, thereby providing a means to estimate the resulting segment capacity. The first 15 min were used as a warm-up period to ensure the traffic had stabilized before data collection. The VISSIM default random vehicle arrivals were also used in this study. All vehicle types assume similar speed distribution on entering the roadway network, and therefore the desired speeds of HDVs and CAVs in the network were not entirely the same by following a pre-specified desired speed distribution. However, the speed of a CAV during the operations may also be determined by other factors, such as the CACC protocol, if this CAV becomes a platoon follower. To estimate the resulting capacity, we used the prebreakdown flow rate defined by the HCM as the 15-min average flow rate immediately before the breakdown event. This was averaged over all simulation replications.

CAV Modeling

The CACC car-following models developed in this study were based on a well-accepted study by Milanes and Shladover (*20*), which has been previously used (*21*). Interested readers should refer to those studies for model details. We adapted their model in VISSIM implementation to include testing various settings of intra-platoon gaps for sensitivity analysis. We also developed additional CACC protocols in VISSIM API for operations of CACC vehicles to form or leave platoons and perform lane following under various conditions, as shown in Figure 2. We assumed a maximum platoon length of 10 vehicles. This eliminates disturbances which could hinder the performance of the algorithm at on- and off-ramps (if any) as a result of the necessary lane changes. If the platoon length is too high, it would make merging difficult and causes unreliable communication between the leader and vehicles toward the end of the platoon, and if it is too low, it reduces the capability of the CACC implementation. In a previous study by the California PATH's program (link below), researchers tested the effect of various platoon lengths of 5, 10, 15, 20, and 25 on the mainline throughput at freeway on-ramp and off-ramp areas. It was found that the best maximum platoon length should be between 10 and 15, although 10 was recommended so as to lower the probability of traffic breakdown for challenging cases where the on-ramp demand may be very high (*22*). A basic introduction of the logic is presented for the completeness of the presentation and more detail can be found in Milanes and Shladover (*20*). All model assumptions and parameters used here are within the ranges recommended in the same study.

As shown in Figure 2, the CACC protocol consists of two modes (speed regulation and gap regulation) in which the switching conditions within each mode is based on the regulation of the speed and gap between consecutive CAVs. The purpose of the speed regulation mode is to maintain the user-desired speed when the preceding vehicle is beyond a pre-set gap (i.e., a time gap larger than 2 s from the preceding vehicle). In this case, the controller uses the vehicle acceleration model defined in Equation 1 to control the speed.

$$a_{sv} = k_1\left(v_f - v_{sv}\right) \tag{1}$$

where

k_1 (assumed as 0.4 s^{-1}) is the control gain being the difference between the FFS and the subject vehicle's current speed,

a_{sv} is the acceleration recommended by the controller to the subject vehicle (m/s^2),

v_{sv} is the current speed of the subject vehicle (m/s), and

v_f is the FFS (m/s).

If the preceding vehicle is an HDV, the subject CAV will switch to the ACC mode to regulate the driving behavior. If the subject CAV is too close to the preceding vehicle (i.e., the detected gap is smaller than a given minimum following threshold, that is, a time gap smaller than 1.5 s from the preceding vehicle), it will switch to the ACC gap regulation mode to maintain a safe following time gap t_{hw}, as shown in Equation 2. Otherwise, the CAV will repeatedly implement previous control logic to ensure consistent driving behavior.

$$a_{sv} = k_2(d - t_{hw}v_{sv} - L) + k_3(v_l - v_{sv}) \tag{2}$$

where $k_2 = 0.23s^{-2}$ and $k_3 = 0.07s^{-1}$ are control gains on following distance difference and speed difference, respectively (Liu et al., 2018). The headway d, preceding vehicle length L, and preceding vehicle speed v_l are considered in Equation 2.

If the preceding vehicle is a CAV, the subject vehicle will switch to the CACC mode and communicate with the preceding vehicle to exchange critical information (e.g., speed, location, platoon size). Equations 3 and 4 are used for CACC following. If the length of the previous CACC platoon is less than the maximum allowable platoon length, the subject CAV will catch up with the preceding CACC platoon and become a platoon follower; therefore the intra-platoon gap t_2 (i.e., different values used in this study for aggressive, normal, and conservative CACC following capability) is applied to tightly follow the preceding CAV. Otherwise, the subject CAV becomes a CACC platoon leader and applies the inter-platoon gap t_1 (1.5 s in this study) to follow the preceding CAV. The specific regulation mode depends on the actual time gap between the subject CAV and its preceding CAV. If the time gap is larger than a given threshold (2 s), the subject CAV will apply speed regulation mode, as shown in Equation 1. Otherwise, it will apply the CACC gap regulation mode to keep a safe following distance with the determined following gap (i.e., inter-platoon gap or intra-platoon gap) by implementing Equations 3 and 4,

$$v_{sv}(t) = v_{sv}(t - \Delta t) + k_p e_k(t) + k_d \dot{e}_k(t) \tag{3}$$

$$a_{sv}(t) = \frac{(v_{sv}(t) - v_{sv}(t - \Delta t))}{\Delta t} \tag{4}$$

where

k_p and k_d (assumed as 0.45 s^{-1} and 0.0125 respectively) are the control gains for adjusting the time gap between the subject vehicle and the preceding vehicle,

e_k is the time gap error defined as $e_k(t) = d(t - \Delta t) - t_1 v_{sv}(t - \Delta t) - L$, $\dot{e}_k(t) = v_l(t - \Delta t) - v_{sv}(t - \Delta t) - t_l v_{sv}(t - \Delta t)$, and

t_1 is the constant time gap between the subject vehicle and the last vehicle in the preceding CACC platoon (assumed as 1.1 s in this study).

As a result of the linearity of the above models, the vehicles cannot handle emergency braking to avoid collisions. The forward collision warning algorithm (*23*) developed by the Collision Avoidance Metrics Partnership (CAMP) is included in the C/ACC car-following modes to determine whether the gap between the subject vehicle and the preceding vehicle is sufficient for safe car-following. If the crash warning is activated, it implies that a crash will happen if both the subject vehicle and the preceding vehicle keep their current acceleration speeds for the next few seconds. The algorithm will use a conventional car-following model (e.g., Wiedermann 99) that is guaranteed collision-free to generate emergency deceleration commands until the crash warning is deactivated.

The A.M. algorithm used in this study is adopted from the VISSIM 11 advanced merge function and described below. The objective of the A.M. algorithm is to coordinate the mainline and merging traffic using V2V and V2I technologies. When a merging vehicle is detected (regardless of whether it is an HDV or a CAV), a gap is created on the mainline that can accommodate the merging vehicle. The system informs the mainline vehicles to cooperatively change to another lane away from the merging vehicle's targeted lane or to slow down slightly to create the required gap. A.M. can be a stand-alone capability of CAVs in this study such that the effects of A.M. alone can be evaluated. The CAVs can also be equipped with CACC and A.M. capabilities at the same time, referred to as "CACC + A.M." HDVs are only regular drivers, and we do not assume that they have A.M. or other advanced driving capabilities.

Simulation Test Scenarios

As previously discussed, the simulation network was first calibrated to match the HCM capacity values. Capacity, being the performance measure of interest in this study, was estimated for different scenarios. For all scenarios tested, the market penetration rate (MPR) was varied from 0% to 100% at 20% increments.

For CACC simulation, three levels of the intra-platoon gap were used in our study: aggressive (0.6 s), normal (following a distribution), and conservative (1.1 s). All these gap settings were applied in the BFS network evaluation. To control the total number of simulation runs, only the "normal" gap-setting was used for FMS and FWS because this is the most realistic scenario. For the "normal" gap settings, we adopted intra-platoon gap distribution specified by Nowakowski et al. (*24*), where the drivers in a survey test chose a time gap of 0.6 s for the 57% of the time they were in car-following, 0.7 s for 24% of the time, 0.9 s for 7% of the time, and 1.1 s for 12% of the time.

Specifically, for BFS, we tested two different lane configurations; two- and three-lane mainline and starting capacities of 2,400, 2,100, and 1,800 pcphpl. Additionally, we evaluated the impact of ACC-equipped vehicles, that is, isolated AVs that adopt commercial automated following behavior, with empirical models also calibrated in Goñi-Ros et al. (*11*), which states that the commercial ACC behavior is conservative and causes string instability. The ACC-equipped vehicles in this study also have the same car-following logic as the CACC already described. However, they do not form platoons as a result of the absence of vehicle communication. In essence, they are stand-alone vehicles. For the FMS, we tested two-lane mainline with a single lane on-ramp and volume-to-capacity (v/c) ratio of 0.8 and 1.0 for mainline traffic. The on-ramp volume was varied from 300 vehicles per hour (vph) at 200 vph increments until a stable capacity was reached for each scenario. In the case of the FWS, we used the three-lane weaving segment, as stated earlier, and performed tests using volume ratios (V.R.) of 0.2, 0.3, and 0.4. The V.R. is the ratio of weaving traffic to non-weaving traffic, given in the HCM as follows:

$$\text{V.R.} = \frac{V_{\text{RF}} + V_{\text{FR}}}{V_{\text{RF}} + V_{\text{FR}} + V_{\text{FF}} + V_{\text{RR}}} \tag{5}$$

where the subscripts indicate the direction of flow, for example, from ramp to freeway, denoted as RF or from the freeway to the ramp, denoted as FR. All the scenarios for FMS and FWS were evaluated with and without the A.M. algorithm.

Capacity Adjustment Factor Estimation

The CAF is estimated as the ratio of the capacity of the evaluated scenario to that of the base capacity. The HCM exhibit 12-6 (*25*) provides the relationship between the base segment capacity and CAF in Equation 6 as

$$c_{\text{adj}} = c^{*}\text{CAF} \tag{6}$$

where c_{adj} = adjusted capacity (pcphpl),
c = base segment capacity (pcphpl), and
CAF = capacity adjustment factor (unitless).

Conventionally in HCM, capacity estimates resulting from the effects of recurring or non-recurring events are usually lower than the base capacity since base capacity reflects ideal conditions (e.g., only passenger cars, clear day, level terrain, etc.). Therefore, the resulting CAF is typically less than 1.0. However, in the case of CAVs, it is expected that the gradual penetration will improve the traffic conditions rather than worsen them; therefore, the expected CAF would be greater than 1.0.

In the final part of this study, we developed a simple but efficient empirical model that accepts certain inputs and predicts the capacity as a function of the inputs. The resulting value is the same as the CAF, which can be used as a multiplier term similar to the one provided in Equation 2. The regression model can be easily integrated with any existing software for the HCM methods. Both CAF tables and regression models enable policymakers to make a quick but reliable estimation of the future capacity of the roadway segment based on selected factors.

Results

Effects of CACC on Traffic Flow

The fundamental diagram (FD) has been used to understand traffic flow for decades. It spells out the basic principles behind the operations of freeway traffic and can also serve as a means for capacity estimation. While past studies (*4*, *7*) have studied the effect of CAVs on the FD and established that there is the potential of removing the congestion region as a result of CAV stability and coordination, we investigate the question from a different perspective. With different roadway starting capacities, we hypothesize that even though CAVs can remove the congestion region, the nature of human drivers in the traffic stream will have an effect on what CAV penetration removes the congested regime. To test this, we conducted a simulation of the FMS using a lower base capacity to compare the behavior of the FD between high and low starting capacities. The results for each starting capacity at each CAV penetration is provided in Figure 3. It confirms earlier findings that CAVs can smoothe out congestion. However, the results provide additional insights and indicate that the smoothing effect of CAVs are only equal across all roadway scenarios when the market penetration is 80% as a result of the dominant existence of CACC vehicles in the traffic stream.

Effects on Basic Freeway Segments

Figure 4 shows the capacity of BFS relative to the MPR of CACC-equipped vehicles. First, the results show that for all the gap-setting used in this study (e.g., normal, conservative), the capacity increases with respect to the MPR. More interestingly, they all follow a quadratic trend, which indicates that the capacity increase is faster as the MPR of CACC becomes larger. Similar insights have also been established in past studies (*26*). However, the aggressive CACC intra-platoon gap results in higher capacity effects. This is logical because tighter headways between vehicles directly affect capacity positively. The conservative scenario, on the other hand, has the lowest impact. Comparing the capacity values for different gap settings for each MPR, at 20% MPR, the effects of CACC are not very different from each other, with the aggressive scenario only 1.2% higher in capacity than the conservative scenario. As the MPR increases, we observe a gradual increase in the margin between the two extreme CACC settings, and at 100% MPR, a 17% margin is obtained. It should be noted that these results are for the scenarios with a base capacity of 2,400 pcphpl.

On further exploring the capacity effects relative to the base capacities, we obtain even more interesting insights. For example, the results from the 1,800 pcphpl base capacity show that the initially quadratic trend of capacity improvement smoothes out to become a more linear trend. This means that, as a result of lower base capacity, the effect of CACC is relatively constant as MPR increases, and the capacity benefits are more pronounced even under low MPRs.

At the 1,800 pcphpl base capacity scenario, we examine the difference between the capacity effects of different gap settings. It is interesting to find that, instead of the 1.2% difference obtained from the 2,400 pcphpl base capacity scenario for 20% MPR, there is a 7% difference in the 1,800 pcphpl scenario. Moreover, at 100% MPR, the capacity difference for the two extreme gap settings for the two starting capacities are the same (17%). This further establishes the earlier statements: CACC has higher benefits at lower MPR for roadways with lower capacities.

Furthermore, there are two BFS configurations analyzed in this study: two- and three-lane segments. The capacity improvements are also examined for both configurations. In summary, for all the scenarios, at all MPRs, regardless of the base capacity, the result for the three-lane BFS is slightly lower than that for the two-lane segment. This directs attention to the effect of lane changing activity on freeway capacity. The per-lane capacity of the freeway segment decreases as the number of lanes increases. However, the differences between the two-lane and three-lane scenarios are quite small, partially because of the capability of CACC strings to absorb disturbances caused by lane changes. Also, this result sheds light on future CACC operations that it is preferable to limit or discourage lane changes to maintain stable traffic flow and high capacity.

While this study focuses on the effects of CAV, we also conducted experiments on ACC, the effects of which are shown in Figure 4. The motivation to include ACC results is to show the importance of connectivity in traffic capacity enhancement. First, it is observed that, for a base capacity of 2,400 pcphpl, there is a decrease in freeway capacity as the percentage of ACC increases. This is because the ACC performs worse than HDVs in traffic. ACC systems are built for comfort and safety is a higher priority for them, which generally results in more conservative behavior. In the 1,800 pcphpl scenario, however, we observe an increase in capacity as the penetration of ACC increases. This is because even though the ACC systems are designed to be conservative, their headways are still lower than the headways for HDVs, leading to capacity improvements. This suggests that ACC systems of this nature can perform better than HDVs under non-ideal conditions, likely as a result of the deterministic behavior of ACCs that stabilizes the traffic flow. The result for ACC in the case of 2,100 pcphpl base capacity is quite interesting. We obtain a decrease in capacity for

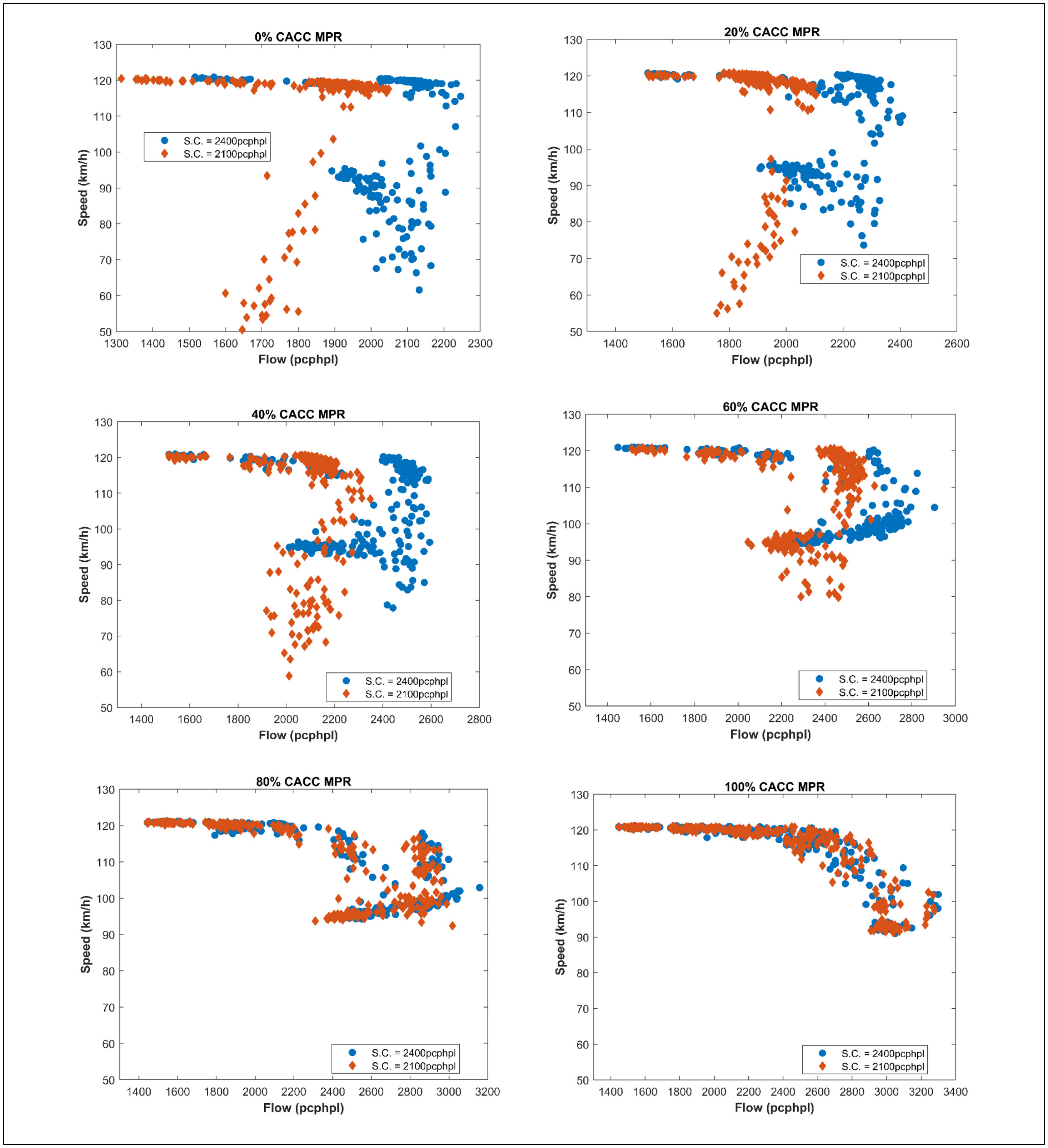

Figure 3. Fundamental diagrams for each CACC MPR with different mainline starting capacities.
Note: CACC = cooperative adaptive cruise control; MPR = market penetration rate; pcphpl = passenger cars per hour per lane; S.C. = starting capacity.

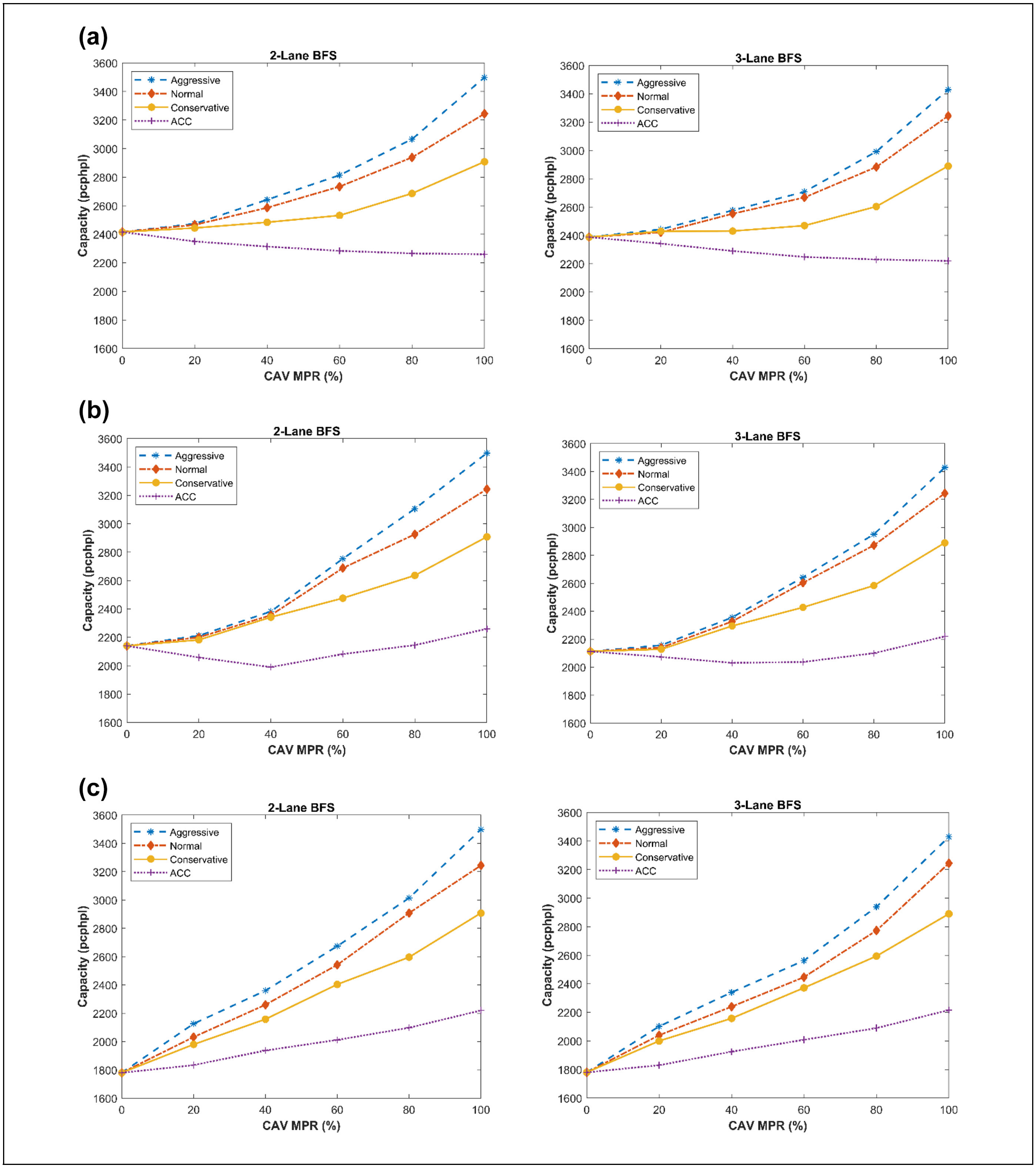

Figure 4. Results for basic freeway segments: (*a*) base capacity = 2,400 pcphpl; (*b*) base capacity = 2,100 pcphpl; and (*c*) base capacity = 1,800 pcphpl.

Note: ACC = adaptive cruise control; CAV = connected and automated vehicles; MPR = market penetration rate; pcphpl = passenger cars per hour per lane; BFS = basic freeway segment.

Table 1. Capacity Results for Freeway Merge

	Market penetration rate (MPR)					
Capacity (vphpl)	0%	20%	40%	60%	80%	100%
No on-ramp (BFS)	2,416	2,466	2,586	2,734	2,938	3,244
CACC	2,206	2,242	2,371	2,556	2,932	3,296
% difference	(–9%)	(–10%)	(–9%)	(–7%)	(0%)	(2%)
CACC + A.M.	2,206	2,353	2,439	2,662	2,976	3,306
% difference	–9%	–5%	–6%	–3%	1%	2%
A.M. capacity	2,206	2,231	2,280	2,330	2,346	2,353
% difference	(–9%)	(–11%)	(–13%)	(–17%)	(–25%)	(–38%)

Note: vphpl = vehicle per hour per lane; BFS = basic freeway segment; CACC = cooperative adaptive cruise control; A.M. = advanced merge.

the first few penetration rates, then an increase thereafter. The initial drop in the capacity is a result of the added variance of driver behavior as a result of the distinct behavior between ACC vehicles and HDVs. The eventual increase in capacity then occurs because of the stability effect when ACC vehicles constitute most of the system.

Effects on Merge Segments

The results of merge segments are provided below in relation to CAV MPR, CACC capabilities, A.M. capabilities, the mainline demand, and the on-ramp demand. Recall that the segment configuration is a two-lane mainline and a single lane on-ramp. The acceleration lane is 500 ft, starting 1.5 mi downstream of the segment starting point. Table 1 provides the general capacity estimates based on different scenarios for the segment. The "No on-ramp" scenario is the capacity of the segment under the scenario with zero ramp demand. This is the same as the results obtained in the two-lane BFS scenario. However, every other scenario was simulated by varying the on-ramp demand gradually from low (300 pcphpl) to high volumes. The "CACC" scenario indicates implementing only the CACC application for the CAVs in the traffic stream. The "CACC + A.M." scenarios involve equipping the CAVs with both CACC and A.M. capabilities. The "A.M." scenario indicates equipping CAVs with only A.M. capability. Each of these other scenarios was compared with the "No on-ramp" scenario, and the percentage difference is provided in the table as well.

As expected, merging traffic causes disturbances which translate into lower capacities for the fully HDV traffic scenarios (0% MPR). Even with increasing CAV penetration, the resulting capacity still falls below the "No on-ramp" scenario. However, on reaching 80% MPR of CAVs, different results are obtained for scenarios with CACC technology. At 80% MPR, the effect of improved vehicle capabilities allows much better coordination between mainline traffic and merging traffic, thereby offsetting the reduction in capacity as a result of the initial merging disturbance. This is because the CACC following behavior (i.e., control algorithms) can make vehicles react faster and more stably to absorb disturbances from the downstream traffic. More specifically, the 7% reduction in capacity from merging disturbance was removed, and even at 100% MPR, the mainline was able to accommodate about 2% more vehicles merging from the ramp. In essence, as the MPR increases, the effect of merging disturbance reduces as a result of CACC coordination.

The only exception to these results is the "A.M." scenario, which involves CAVs with only advanced merging capabilities (i.e., no CACC). Although there are improvements from increased MPR of CAVs, the benefits are still low to offset the capacity reduction from the initial merging disturbances. This further establishes the potential benefits that can be obtained from CACC vehicle operations.

With the effect of CACC already established, it is important to also examine the effect of an added A.M. capability. This is done by comparing the "CACC" and "CACC + A.M." scenarios. The effect of A.M. is more pronounced at lower MPRs. This may be a result of more HDVs in the traffic stream, which provides more gaps for merging purposes. At high MPR, CACC-equipped vehicles are already traveling at smaller gaps with more coordination, thereby leaving not much room for A.M. possibilities. The greatest improvement from A.M. capability relative to CACC is 5%, which occurs at 20% MPR. It is also noted from the comparison that the main capacity benefits from CAVs, as expected, comes from the stable platoons with shorter headways.

To further explore the effect of on-ramp demand on segment capacity, we analyzed the variation in the resulting capacity as a measure of the on-ramp demand and enhanced vehicle capabilities. It is reasonable to assume that different on-ramp demand provides a different segment capacity (e.g., the turbulence effects of an on-ramp with a demand of 100 vehicles will vary more drastically than in the case of an on-ramp with 500 vehicles). Besides, changes in mainline traffic demand also provide interesting results. For instance, by having the mainline demand as 80% of the estimated capacity for each MPR, the unused portion of the roadway should be able to

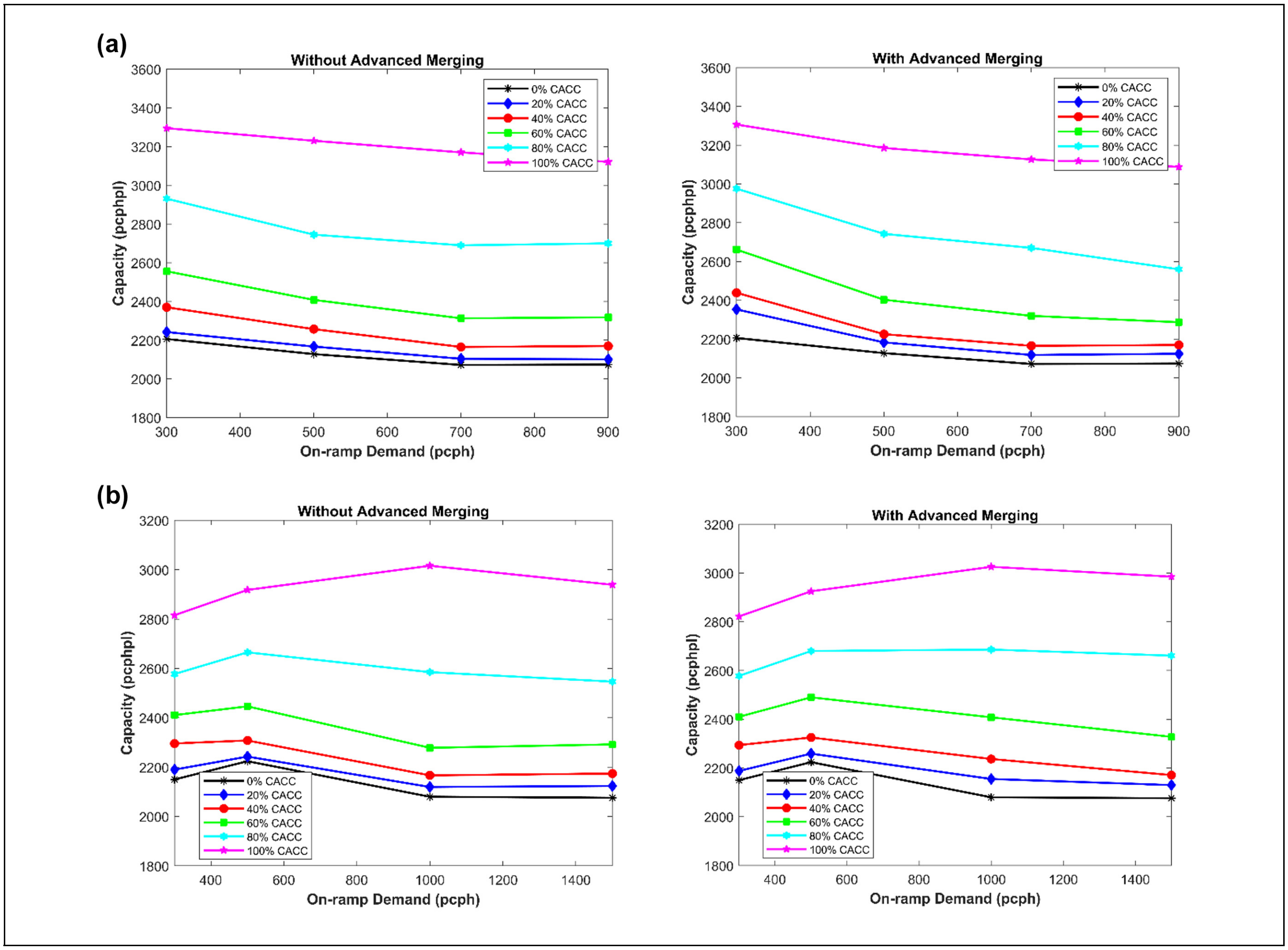

Figure 5. Capacity trend with increasing on-ramp demand for each CACC market penetration: (*a*) 100% mainline demand; and (*b*) 80% mainline demand.
Note: pcphpl = passenger car per hour per lane; pcph = passenger car per hour; CACC = cooperative adaptive cruise control.

accommodate more merging vehicles. Figure 5 indicates the capacity trends as on-ramp demand increases for each CAV MPR. Both scenarios were simulated with and without A.M. capabilities of CACC-equipped vehicles.

From the 100% mainline demand scenario, the first interesting observation is that at low CAV MPR, the segment is unable to maintain its capacity, but instead reduces under increasing on-ramp demand until it reaches a stable value. However, at high CAV MPR, the segment can maintain the same capacity longer under increasing on-ramp demand before reaching stable capacity conditions. These results indicate that careful consideration should be put in place because there are different segment capacities for different on-ramp demand, even in cases with fully HDV traffic. The segment capacity is not constant across all on-ramp demand volumes. The capacity of the merge segment can decrease when the demand from the on-ramp is very high. This is similar to findings from past related studies (*27*, *28*).

On the other hand, the 80% mainline demand confirms the initial expectation that the unused portion of the mainline can accommodate more merging vehicles. In reality, the 20% volume that was removed from the mainline traffic was recovered from the merging traffic. Even more importantly, if the 20% mainline demand was removed at 0% CACC MPR, the segment could only accommodate about 300 vehicles, but if it was removed at 100% CACC MPR, the segment could accommodate about 1,000 more vehicles as a result of CACC operations. The trend obtained at low CAV MPR for 80% of mainline demand indicates that more vehicles are entering the mainline under this condition. However, it should also be noted that similar to the 100% mainline demand, the capacity benefits eventually fall and then reach a stable value, also reiterating the findings that different on-ramp demand can result in different segment capacities.

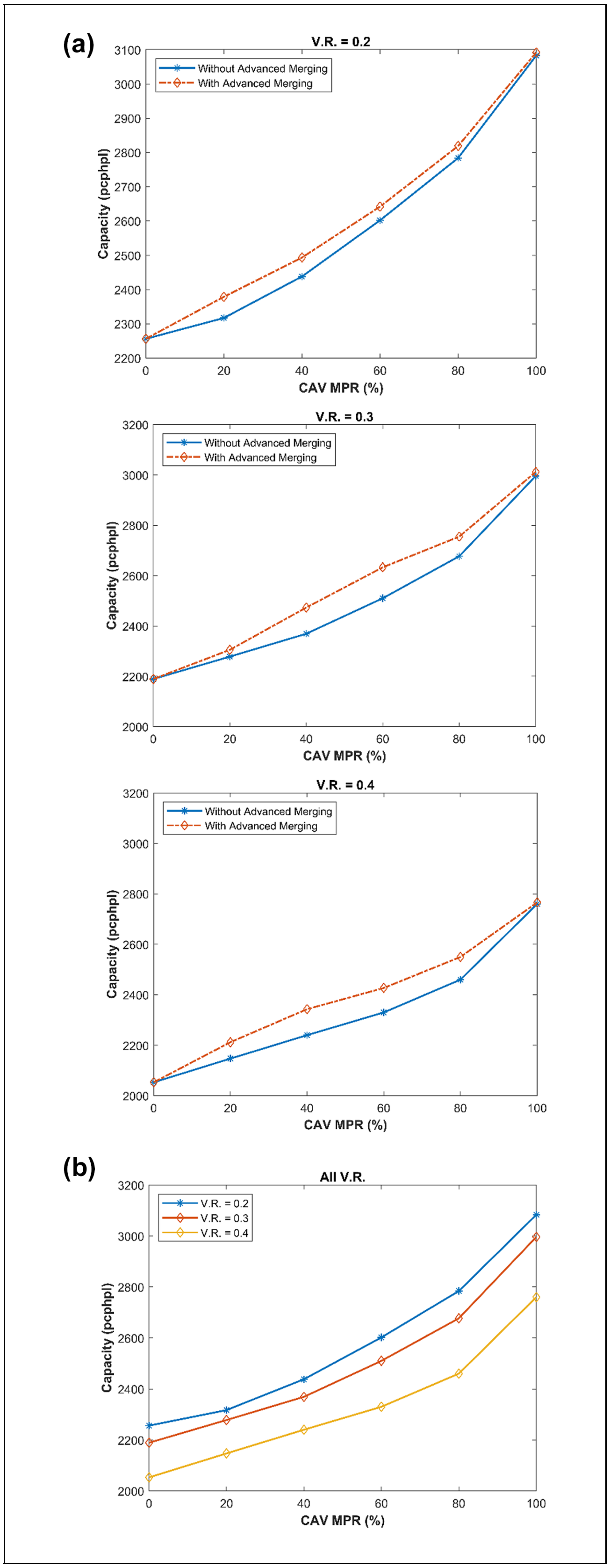

Figure 6. Freeway weaving segment results with varying V.R.: (*a*) V.R. = 0.2, 0.3, and 0.4; and (*b*) all V.R. combined (without A.M.).
Note: V.R. = volume ratio; A.M. = advanced merge; CAV MPR = connected automated vehicle market penetration; pcphpl = passenger car per hour per lane.

We established that at 80% of mainline traffic, the merge segment can accommodate more vehicles from the ramp. To ensure the practicality of the result, a congestion analysis was conducted on the mainline and on-ramp traffic. The results indicated that the on-ramp was not suffering from any level of congestion as a result of oversaturation. The mainline traffic was only having some level of delay, which is as expected as a result of merging disturbances.

Effects on Weaving Segments

Weaving segment results are provided in Figure 6. As stated earlier, three V.R. levels were tested in this study. Using each V.R., we tested the effect of MPRs of CACC-equipped vehicles with and without A.M. capabilities. This was simulated using the "normal" gap settings for CACC-equipped vehicles.

The capacity increase obtained from FWS also follows a quadratic trend, which is similar to all the other scenarios with similar simulation setups. However, the gradient of the curve is steeper as a result of the lower base capacity of the weaving segment. It should be noted that, without any weaving volume, the capacity of the segment is 2,400 pcphpl, and with the weaving demand, the capacity drops, even at 0% CAV penetration, as a result of the friction effects. Therefore, the base capacity reduces from the original 2,400 to 2,256 pcphpl. As previously mentioned, the simulation model was calibrated, such that the segment capacity with 0% MPR was similar to the HCM capacity given for the weaving segments.

Furthermore, examining the effect of V.R. on capacity (as shown in Figure 6*b*), it is observed that, similar to past studies (*29*), as the V.R. increases, the resulting capacity decreases. A higher V.R. indicates a higher volume of vehicles trying to make lane changes from the freeway to the ramp and vice versa. Lane changes directly affect capacity, and this is also established from the BFS analysis. At 100% CACC, the reduction in capacity is as high as 8% as a result of increasing V.R. from 0.3 to 0.4.

A.M. capabilities have generally been observed to increase capacity in this study. The difference between the experiment here and the one conducted for FMS is that there is more lane changing activity as a result of the weaving. Results obtained here indicate that the A.M. capability is only effective between 20% and 80% CAV MPR, with the biggest benefits at 40% and 60%. The A.M. requires qualified gaps to function properly. Most of the large gaps are only available when HDVs are in the traffic stream. The tight gaps from CAVs from platooning actually limit the A.M. capabilities.

Capacity Adjustment Factor Results

The penultimate objective of this study was to obtain CAFs for different roadway configurations under varying CAV conditions. Table 2 shows the result of the

Table 2. CAF Results for All Freeway Configurations Tested

Basic freeway segment			
MPR/S.C.	2400	2100	1800
0	1.00	1.00	1.00
20	1.02	1.02	1.15
40	1.07	1.10	1.27
60	1.13	1.25	1.40
80	1.22	1.37	1.60
100	1.35	1.53	1.82
Freeway weaving segment (without A.M.)			
MPR/V.R.	0.2	0.3	0.4
0	1.00	1.00	1.00
20	1.03	1.04	1.05
40	1.08	1.08	1.09
60	1.15	1.15	1.13
80	1.23	1.22	1.20
100	1.37	1.37	1.34
Freeway weaving segment (with A.M.)			
MPR/V.R.	0.2	0.3	0.4
0	1.00	1.00	1.00
20	1.05	1.05	1.08
40	1.11	1.13	1.14
60	1.17	1.20	1.18
80	1.25	1.26	1.24
100	1.37	1.38	1.35
Freeway merge segment			
MPR	CACC	CACC + A.M.	A.M.
0	1.00	1.00	1.0
20	1.02	1.07	1.01
40	1.07	1.11	1.03
60	1.16	1.21	1.06
80	1.33	1.35	1.06
100	1.49	1.50	1.07

Note: MPR = market penetration rate; S.C. = starting capacity; A.M. = advanced merge; CACC = cooperative adaptive cruise; CAF = capacity adjustment factors; V.R. = volume ratio.

CAF for all the configurations tested in the simulation. Note that as a result of similar two-lane and three-lane results, we combined them and took the average to represent the BFS capacity. The "A.M." indicates scenarios with only CAVs with A.M. capability in the network, and the MPR represents the portion of CAVs with the A.M. capability. In the "CACC" scenario, none of the vehicles have A.M., and the MPR indicates the portion of CAVs with the CACC capability. The "CACC + A.M." scenario is the same as the CACC scenario except that the CAVs in the network now have A.M. capability. The "CACC + A.M." MPR represents the percentage of vehicles with both capabilities.

Finally, to derive empirical models that quantitatively establish the relationship between the capacity effect of CAVs and different freeway configurations, we conduct a regression analysis of the obtained results. Three different empirical relationships are provided for each freeway segment under consideration. The variables provided are significant at a 95% confidence interval on the CAF. The regression result further shows that even though our analysis shows slight capacity decreases for three-lane compared with two-lane BFS, the number of lanes is still not a significant predictor (p-value = 0.16) of the resulting capacity. A.M. is significant for both FMS and FWS.

The R-square values for the three regression models are obtained as 0.89, 0.86, and 0.97 for BFS, FMS, and FWS, respectively, indicating excellent fits. The relationship between the CAF and the independent variables can, therefore, be expressed as

$$f_{\mathrm{CAV,BFS}} = \left[1.077 + 0.043P_{\mathrm{PLT}}\left({}^{*}10^{-2}\right) - 0.016G_{\mathrm{IP}} - 0.031\mathrm{S.C.}\left({}^{*}10^{-3}\right)\right]^{10} \quad (7)$$

$$f_{\mathrm{CAV,FMS}} = \left[0.994 + 0.033P_{\mathrm{PLT}}\left({}^{*}10^{-2}\right) - 0.013\mathrm{R.D.}\left({}^{*}10^{-2}\right) + 0.004\mathrm{A.M.}\left({}^{*}10^{-2}\right)\right]^{10} \quad (8)$$

$$f_{\mathrm{CAV,FWS}} = \left[1.093 + 0.033P_{\mathrm{PLT}}\left({}^{*}10^{-2}\right) - 0.051\mathrm{V.R.} + 0.002\mathrm{A.M.}\left({}^{*}10^{-2}\right)\right]^{10} \quad (9)$$

where

P_{PLT} is the percentage of platoon/CACC-equipped vehicles in the traffic stream,

G_{IP} is the intra-platoon gap,

S.C. is the starting capacity, R.D. is the ramp demand,

V.R. is the V.R., and

A.M. is the percentage of vehicles with A.M. capability.

For the case where G_{IP} follows a distribution, we recommend using the expected value of 0.71, which represents the average of the distribution, also used in Liu et al. (*30*). $f_{\mathrm{CAV,BFS}}$, $f_{\mathrm{CAV,FMS}}$ and $f_{\mathrm{CAV,FWS}}$ are the CAFs for basic freeway, freeway merge, and freeway weaving segments respectively. Various variable interactions were tested in developing the empirical model, and they did not improve the model performance.

Conclusions and Future Research

CAV technologies are set to revolutionize the nation's transportation systems in relation to safety and operational features. A great deal of research and testing is under way to specifically equip vehicles and roadways with advanced technologies. CAVs will be able to communicate with each other, thereby offering improvements in roadway performance in the near future.

However, it is essential to make wise decisions on future implementation strategies. The majority of CAV studies are still based on simulation because of the cost of conducting a naturalistic study of such magnitude. This usually requires a large amount of simulation that may be time-consuming. To address this, the objective of this study was to evaluate different possible implementation scenarios and provide decision-makers with a quick evaluation method for assessing the effects of different implementation possibilities. In this study, we considered some of the most common geometric and traffic characteristics of roadways, evaluated the future effects, and then provided an empirical model that could be used to assess the benefits of different future CAV implementation.

For the basic freeway segments, we analyzed the effect of CACC-equipped vehicles using different starting capacities. The results confirm the findings of similar past studies and also provided some new findings. The capacity impact on CACC follows a quadratic trend. However, in cases of lower starting capacities, the trend begins to change to a linear trend. This infers that the capacity impacts are not the same across all jurisdictions. Therefore, depending on the type of existing roadway users, the capacity increase can sometimes follow a linear trend. We also analyzed the effect of on-ramp demand on merge segment capacity. Results indicated that different roadway capacities are achieved at different ramp demand levels. More interestingly, CACC coordination can potentially reduce the effect of merging disturbance at on-ramps when the market penetrations are high enough. On weaving segments, results showed that the capacity impacts of CACC decrease with an increase in V.R. The weaving disturbances drastically reduces the effects of CACC coordination. Even with an A.M. capability, the effects of weaving intensity were still pronounced.

Future work is required in this study. More complex freeway scenarios such as managed lanes, higher weaving ratio, and two-lane on-ramps may be incorporated in future studies. Other roadway segments, such as urban streets and arterials, could be investigated as well. Additionally, the combined effect of other CAV applications that may potentially be implemented in the near future may be considered in later studies.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: A. Adebisi, J. Ma, Y. Liu, B. Schroeder, A. Morgan, and B. Cesme; data collection: A. Adebisi, J. Ma, and Y. Liu; analysis and interpretation of results: A. Adebisi, J. Ma, Y. Liu, B. Schroeder, A. Morgan, and B. Cesme; draft and manuscript preparation: A. Adebisi, J. Ma, Y. Liu, and B. Cesme. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

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